AUV Turbulence Measurements in the LOCO Field Experiments

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LONG-TERM GOAL

The long-term goal of this project is to quantify the role of turbulence and fine scale vertical shear and buoyancy on the formation, evolution, and breakdown of thin phytoplankton layers. Particular attention is given to understanding the relationship of the space and time statistics of the physical fields to that of the phytoplankton thin layers.

OBJECTIVES

(1) Quantify the horizontal and vertical structure of turbulence and identify the most probable mechanism of generation and maintenance. Particular attention will be given to the turbulent field arising from the internal wave train. Estimate the micro and fine scale parameters relating to thin layer studies: the turbulent dissipation rate, the buoyancy Reynolds number, the turbulent rms velocity, the turbulent eddy diffusivity, fine scale velocity shear, and fine scale stratification.

(2) Examine the role of turbulence on the evolution of the spatial structure of thin phytoplankton layers.

(3) Quantify the role of physical processes, such as turbulence mixing (diffusion), shear dispersion, and mean current advection on the temporal and spatial distribution and evolution of thin layers in the coastal ocean.

(4) Developing criteria for conditions in which organisms will behave as passive Lagrangian tracers.

APPROACH

The observational approach is to use the Autonomous Underwater Vehicle, T-REMUS, shown in Fig. 1. T-REMUS is a custom designed REMUS 100 vehicle manufactured by Hydroid Inc., containing the Rockland Microstructure Measurement System (RMMS), an upward and downward looking 1.2 MHz ADCP, a FASTCAT Seabird CTD, and a WET Labs BB2F Combination Spectral Backscattering

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14. ABSTRACT
The long-term goal of this project is to quantify the role of turbulence and fine scale vertical shear and buoyancy on the formation, evolution, and breakdown of thin phytoplankton layers. Particular attention is given to understanding the relationship of the space and time statistics of the physical fields to that of the phytoplankton thin layers

15. SUBJECT TERMS

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Meter/ Chlorophyll Fluormeter. In addition, the vehicle contains a variety of “hotel” sensors which measure pitch, roll, yaw, and other internal dynamical parameters.

This suite of sensors on T-REMUS allows quantification of the key dynamical and kinematical turbulent and finescale physical and biological processes (Goodman & Wang, 2009; Wang & Goodman, 2009a, b). The turbulence measurements are made concomitantly with very high spatial resolution measurements of temperature, salinity, and depth. The BB2F sensor system measures chlorophyll fluorescence and optical backscattering at 470 nm and 700 nm wavelength. The turbulent and finescale parameters which can be estimated from the data collected by the T-REMUS include: the turbulent dissipation rate, the buoyancy Reynolds number, the turbulent velocity, finescale velocity shear, and finescale stratification. The thin phytoplankton layers are identified from chlorophyll a using the similar criteria as Dekshenieks et al. (2001).

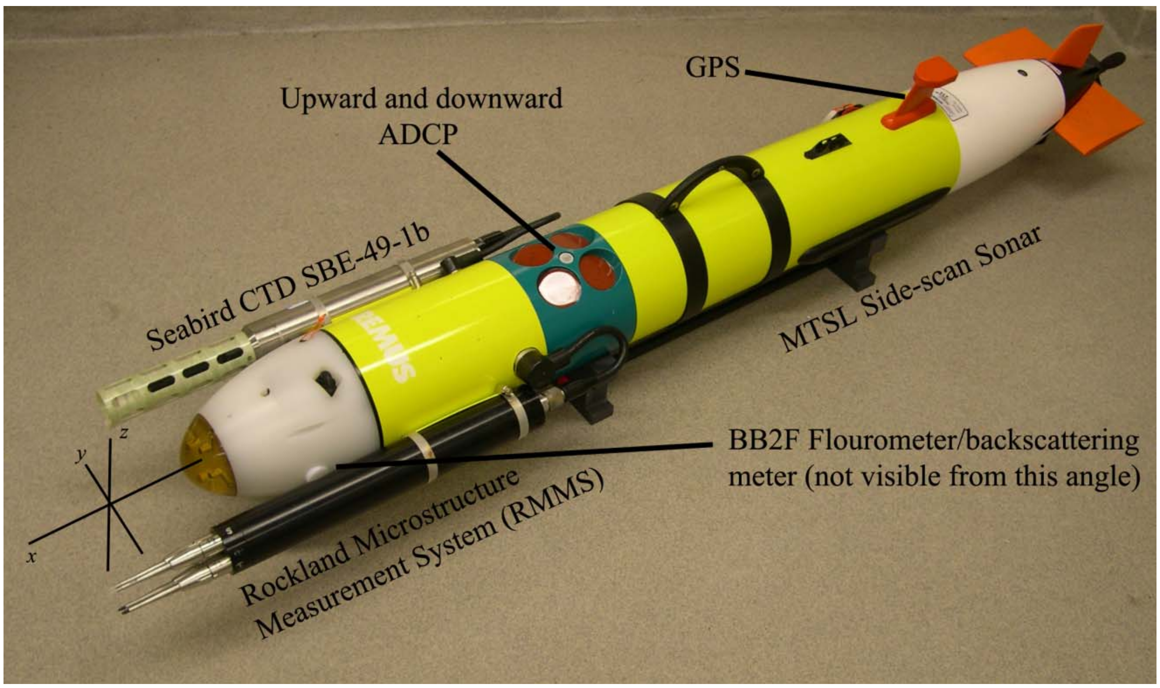

Figure 1, The SMAST T-REMUS Autonomous Underwater Vehicle. It is 2.0 m long, 20 cm diameter, and 63kg mass. Vehicle based sensors are indicated in the figure.

WORK COMPLETED

Two highly successful experiments were completed for LOCO 2005 and LOCO 2006 at the Monterey Bay site, centered near 36.93 N, 121.92W in the immediate vicinity of the fixed LOCO observatory stations deployed by Donaghay and Holliday, Figure 2b. During both LOCO 05 and LOCO 06 the T-REMUS performed flawlessly and had a remarkable 100 % data return. In both year experiments, the chlorophyll a and backscattering data showed significant thin layers. Data processing is completed for both LOCO 05 and 06 experiments with analysis now seriously underway. Using LOCO data sets, four manuscripts have been written. One manuscript “Turbulence Observations in the Northern Bight of Monterey Bay from a Small AUV” has been published (Jun, 2009) by Journal of Marine Systems

(JMS) and one “On the Evolution of the Spatial Structure of a Thin Phytoplankton Layer into a Turbulent Field” has been published (Jan, 2009) by Marine Ecology Progress Series (MEPS). The third manuscript “The dynamical evolution of thin phytoplankton layers in turbulence” has just been accepted (Aug, 2009) for publication by Continental Shelf Research (CSR), LOCO special issue. The fourth one “Sub surface observations of surface waves from an autonomous underwater vehicle (AUV)” has been submitted (Apr, 2009) to IEEE Journal of Oceanic Engineering.

In LOCO 05, the T-REMUS performed a series of box of runs sides 2 to 3 km centered around the location of the principal LOCO moorings (Fig. 2b). The vehicle was operated in a yoyo mode with a descent/ascent angle of 1 degree. This allowed thin layers to be resolved to 2 cm thickness. Eight such runs were performed, four of which were nighttime runs between 11:00 PM and 1: 00 AM, the time period of expected maximum occurrence and intensity of thin phytoplankton layers during LOCO 2005. We will be applying some newly developed theory on how turbulence can affect mobile plankton such as dinoflagellate, Akashiwo Sanguinea, which was found to be present in the observed thin layers.

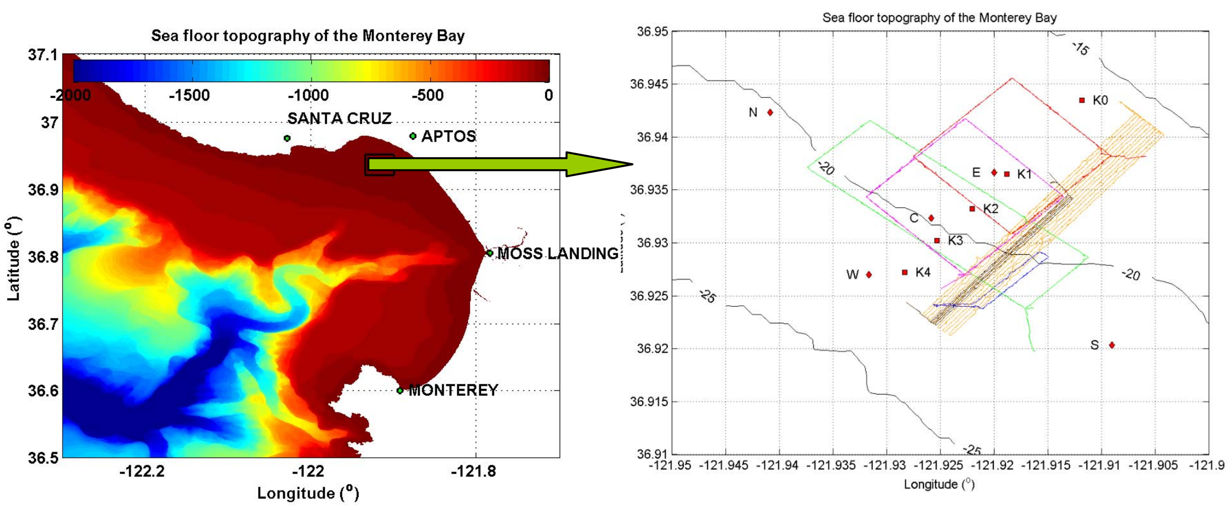

Figure 2, a) Map of the complex topography within and offshore of Monterey Bay. b) Detailed map showing the tracks of the T-REMUS AUV during LOCO. Also showed are the location of the fixed LOCO 2005 and 2006 stations.

In LOCO 06 sampling strategy for the T -REMUS was changed to increase horizontal resolution and to more closely parallel the fixed LOCO moorings, indicated by the salmon-colored lines in Fig 2b. There were 12 continuous AUV tracks which ran parallel to the fixed LOCO observatory stations K0 to K4. These tracks were approximately perpendicular to isobath contours. Each track, 2.5 km in length, took 40 min and alternated between an outbound one and an inbound one. The AUV operated in a 5° yoyo mode with a ground speed of 1.2 m/s. AUV depth ranged from 1.0 m from the surface to 4.0 m above the bottom. Each track consisted of approximately 16 profiles with the horizontal distance between profiles being on average 150 m apart. Four 8-h such data sets were collected during LOCO 06.

We will now very briefly present some results germane to the issue of the spatial structure of turbulence and its role in the evolution of the spatial structure of a thin phytoplankton layer. For this

analysis we examine in detail two particular, 8 h data sets obtained on July 17 and July 24, 2006 respectively during LOCO 06. Fine scale measurements of the horizontal and vertical spatial structure of the surrounding current, density field, chlorophyll a and optical backscattering were obtained simultaneously. This sampling scenario not only allowed a detailed horizontal and vertical map of the turbulent field but also of the surrounding larger scale physical fields which drive the turbulence.
The most significant contributions of the T-REMUS turbulence and thin layers studies can be summarized as follows.

1. Three Dimensional Turbulence Measurements from AUV

Both horizontal and vertical structure of turbulence was measured by T-REMUS AUV at a 5 degree yoyo mode. The experiment took place during a time period of weak wind, little air-sea interaction and weak tidal flow. This allowed me to examine the spatial structure of different regimes and to identify their most probable mechanisms of generation and maintenance. Strong turbulence was consistently measured in the boundary layer, either near the surface or in the bottom mixed layer. The turbulence in the thermocline was very patchy for most periods, except when an internal wave train passed by on July 17 and when a strong tidal flow occurred on July 24.

Figure 3 shows 12 contour plots of buoyancy Reynolds number, $\log_{10}(\mathrm{Re}_b)$ as a function of across isobath range, r, and depth, z for example. Each contour was obtained on the 12 legs shown in Figure 2b. The origin of the abscissa, r = 0, is taken to be at the initial reference point at (36.942, -121.905). The experiment was conducted from 19:00 PDT 17 July 2006 to 03:00 PDT on the next day. The mean location of the profiles used to make these contour plots is indicated by a sequential number on the top of each contour panel. In addition to the buoyancy Reynolds number shown in Figure 3 we also have detailed spatial data on temperature, salinity, density, vector current, dissipation rate, turbulent velocity, chlorophyll-a, and optical scattering at 470 and 700 nm. The buoyancy Reynolds number is defined by

$$\mathrm{Re}_b = \frac{\varepsilon}{\nu N^2}$$

Where ε is the the dissipation rate of turbulent kinetic energy; $\nu = 10^{-6}\ \mathrm{m^2 s^{-1}}$ is the kinematic molecular viscosity; and N the buoyancy frequency. Re_b is a measure of the turbulent spatial dynamic range and is a better indicator of the strength of the turbulent field in a stratified fluid than ε. When $\mathrm{Re}_b > 200$, the turbulent field is fully developed and isotropic (Yamazaki & Osborn 1990). We will use the term "strong turbulence" to refer to that condition. When $\mathrm{Re}_b < 20$, stratification is sufficiently strong such that turbulence ceases to exist (Yamazaki & Osborn 1990). The panels in Fig. 3 show 3 regimes of strong turbulence with $\mathrm{Re}_b > 200$. These are: (1) a near surface regime associated with the warm water intrusion; (2) a bottom mixed layer regime; (3) a mid depth regime of strong vertical density (temperature) gradient. Note the very strong isolated patch of turbulence in what looks to be in the lee of an internal solitary wavelike feature in panel #5. This location of a turbulence patch relative to an internal solitary like wave is similar to that observed by Moum et al. (2003) off the Oregon coast.

Goodman & Wang (2009) have a detailed discussion on the most probable mechanisms for the turbulence generation in the three regimes. During the middle of the experiment at t = 21:30 PDT, a warm water surface intrusion was observed to evolve into a very strong frontal feature in which very strong turbulence occurred nearby. An upslope movement of the bottom mixed layer can be seen by following a near bottom isotherm, for example, the T = 11.2°C isotherm, initially located in panel #1 at the very lower left hand side of the panel. With time, it goes upslope for 900 m in 8 hours at the end of

the experiment. Both the warm water surface intrusion and upslope movement of bottom mixed layer resulted in strong shear driven turbulence. The upslope transport of buoyancy in the most offshore location of the bottom mixed layer was approximately balanced by cross isopycnal turbulent buoyancy flux. Strong turbulence in the thermocline was noted towards the end of the experiment.

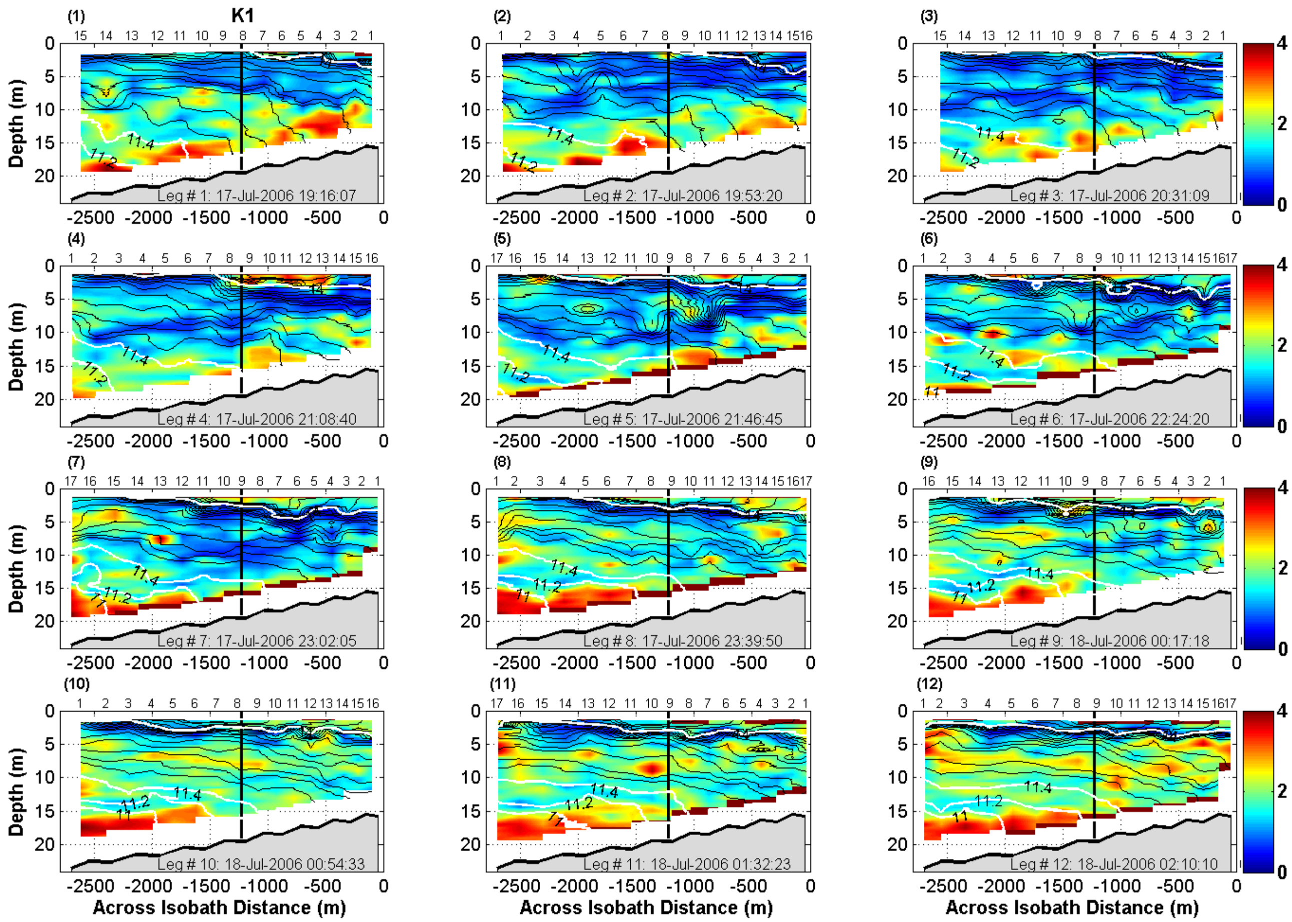

Figure 3, Contour plots of buoyancy Reynolds number* $\log_{10}(\mathrm{Re}_b)$. *Data were obtained from 07:00 PDT 17 July 2006 to 03:00 PDT 18 July 2006. Each contour was obtained on the 12 legs(salmon-colored lines) shown in Fig. 2b. Black contour lines show isotherms with 0.2 °C spacing. The numbers on the top of the contour map indicate profile number, located at their average location. The leg number and beginning time of each leg are showed at bottom of each figure. Isotherms of T = 11, 11.2, 11.4 and 14°C are emboldened in white. The across isobath location of the K1 thermistor chain is shown by the thick black line.

2. Continuous Turbulence Layer Generated from Internal Wave Train

Strong turbulence in the thermocline was noted towards the end of the experiment on July 17 in Fig .3. Using the modal eKdV model of Grimshaw (2001), along with the observed values of internal wave displacement and local buoyancy frequency, indicated that internal wave induced shear and strain were not sufficiently strong to affect the mean local Richardson number. Moreover the largest internal wave induced effects in lowering the local Richardson number were predicted to occur at depths much

shallower than that where the turbulence was observed. However, a theory was developed based on the approach of Moum et al. (2003) to examine the role of internal wave induced vertical strain gradient on inducing shear. A quantity termed the enhancement factor was derived, En, which could be used to quantify the amount of internal wave induced shear induced from the mean flow. It was shown that this effect of internal wave induced vertical strain was sufficiently strong to lower the local Richardson number below 1. Maxima of En occurred at depths where the largest values of thermocline turbulence were observed. At the end of the experiment strong turbulence was noted in the upper 10 m of the water column. Calculation of the effect of this turbulence on the internal wave train suggested a turbulent decay distance of 1.4 km.

3. Thin Layer Vertical Dispersion and Contraction

As shown in Fig. 4, on July 17 2006, a thin layer of chlorophyll a (chl a) was observed throughout the entire experimental period in the thermocline (Wang and Goodman, 2009a). The center of the thin layer deepened with time, crossed isotherms, and then settled into a strong turbulence layer. The observations indicated that the turbulence field itself was constrained to be in a thin layer by the surrounding strong density stratification. The chl a material, acting as a passive Lagrangian tracer, became embedded within the turbulent field. With time, both the turbulent field and the embedded chl a thin layer were observed to collapse vertically. However, in another data set, on July 24 the turbulence in the region of the thin layer was much more intermittent and not confined vertically as in the 17 July case (Wang and Goodman, 2009b). Given the magnitude of κ_ρ and w_e, in the 24 July case turbulence appears to have been an important factor in this weakening of the thin layer. However, unlike the 17 July case since the total vertically integrated thin layer chlorophyll *a* was not conserved other factors such as advection and migration must also be considered in the evolution and weakening of that thin layer.

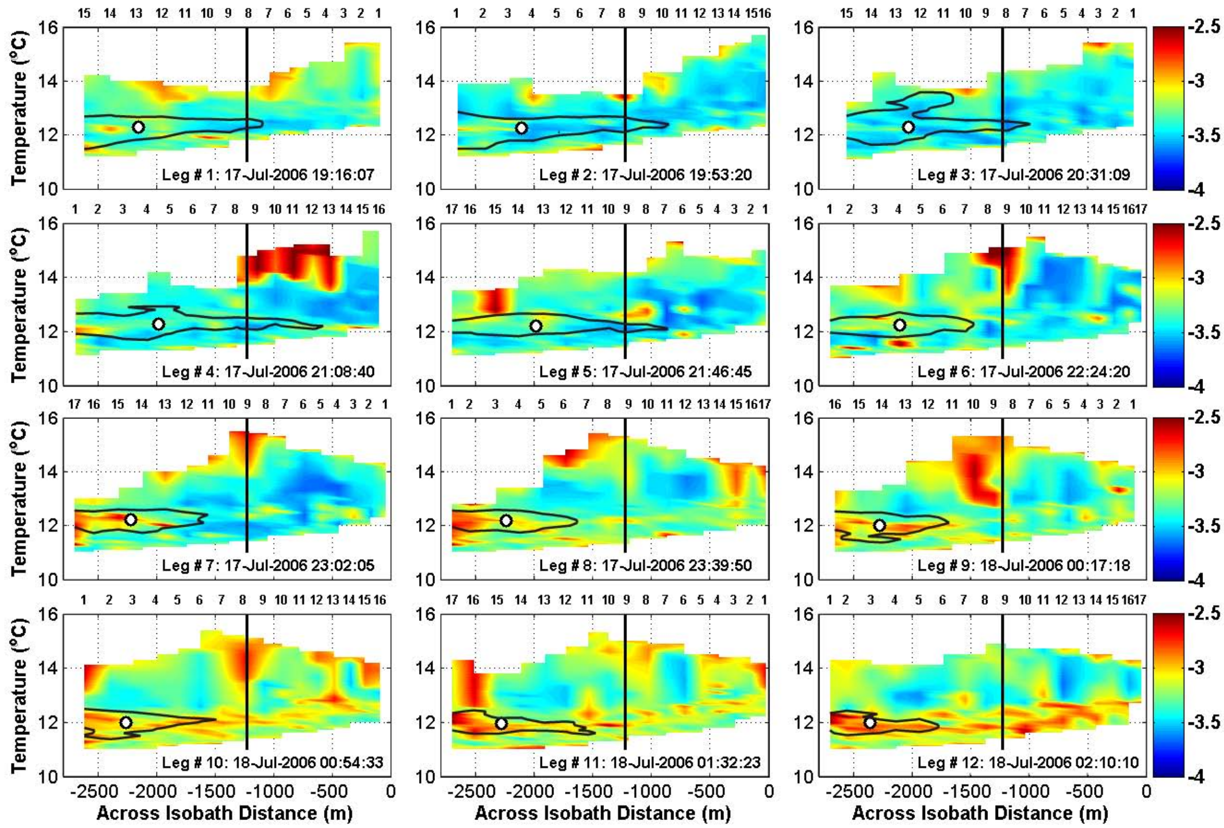

Figure 4, Contour plots of Ozmidov velocity scale $log_{10}w'$ (m s^{-1}) using temperature as the ordinate. Black contour lines: thin layers, defined by the criteria used in Dekshenieks et al. (2001); (o) center of mid-depth thin layer. Time (h:min:s) in panels is Pacific Daylight Time. Numbers above panels: horizontal location of the T-REMUS yoyo profiles (separated 150 m on average).

4. Criteria to Determine the Influence of Turbulence on Thin Layers

In Wang and Goodman (2009a,b) we found that the two key dynamical quantities in determining the role of turbulence on thin layer evolution are the buoyancy Reynolds number (turbulent eddy diffusivity) and the turbulent eddy velocity. The fully developed turbulence is associated $k_\rho > 4 \cdot 10^{-4} m^2 s^{-1}$, (corresponding to $Re_b > 200$) where we have assumed that the mixing efficiency is the standard value of $\Gamma = 0.2$ (Osborn, 1980, Gregg 1987). Estimation of the turbulent eddy velocity, w_e, is critical in assessing whether the turbulent field is intense enough to sweep up biologically based particles and embed them in its flow. If $w_e >> w$, where *w* is an organism motility speed or buoyancy based sinking or rising speed, then we expect the organism to be swept into the turbulent field and follow it as a Lagrangian tracer.

IMPACT/APPLICATIONS

To date, there has been very few in situ studies on the direct effects of small-scale turbulence on thin layers. The platform T-REMUS provides a unique opportunity to quantify the spatial strcuture of the turbulence and fine scale fields and its relationship to thin layer formation evolutiona and breakdown.

Results indicate that thin layers can occur and evolve in both an environment of strong and weak turbulence, which is in contrast to previous studies where thin layers were hypothesized to be only present in locations where the turbulence was weak. Special information regarding the details of turbulence distribution in Monterey Bay are ultimately of importance to understand the dynamics of thin phytoplankton layers. The mechanisms of thin layer evolutions in turbulent conditions should be able to widely apply to other coastal regions.

REFERENCES

Dekshenieks, M.M. Donaghay, P.L. etc. Temporal and Spatial Occurrence of Thin Phytoplankton Layers in Relation to Physical Processes. Marine Ecology Process Series, Vol. 223, pp 61-71, Nov. 2001.

Goodman, L. and Z. Wang, June, 2009, Turbulence observations in the northern bight of Monterey Bay from a small AUV, Journal of Marine Systems, Volume 77, Issue 4, Special issue on marine turbulence, p441-458, ISSN 0924-7963, Doi:10.1016/j.jmarsys.2008.11.004

Gregg, M.C., 1987. Diapycnal mixing in the thermocline: A review. J. Geophys. Res., 92: 5249-5286.
Grimshaw, R., 2001. Internal solitary waves. Environmental stratified flows, Kluwer, Boston, Chapter 1. 1-28.

Moum, J.N., Farmer, D.M., Smyth, W.D., Armi, L. and Vagle, S., 2003. Structure and generation of turbulence at interfaces strained by internal solitary waves propagating shoreward over the continental shelf. J. Phys. Oceanogr ., 33, 2093-2112.

Osborn, T.R., 1980, Estimates of the local rate of vertical diffusion from dissipation measurements. J. Phys. Oceanogr. 10: 83–89.

Wang, Z. and L. Goodman, January, 2009a, Evolution of the spatial structure of a thin phytoplankton layer into a turbulent field. Marine Ecology Progress Series. 374:57-74 Doi:10.3354/meps07738.

Wang, Z. and L. Goodman, 2009b, (in press). The dynamical evolution of thin phytoplankton layers in turbulence. Continental Shelf Research, LOCO special issue.

Yamazaki, H., and Osborn, T., 1990. Dissipation estimates for stratified turbulence. J. Geophys. Res., 95, 9739--9744, 1990.

PUBLICATIONS

Goodman, L., Levine, E.R. and Wang, Z., 2009, (in review). Sub surface observations of surface waves from an autonomous underwater vehicle (AUV). IEEE Journal of Oceanic Engineering.

Wang, Z. and **L. Goodman**, 2009b, (in press). The dynamical evolution of thin phytoplankton layers in turbulence. Continental Shelf Research, LOCO special issue.

Sullivan, J.M., McManus, M.A., Cheriton, O.M., Benoit-Bird, K.J., **Goodman, L.,** Wang, Z., Ryan, J.P., Stacey, M. and Holliday, D.V., 2009, (in press). Layered Organization in the Coastal Ocean: An introdcution to planktonic thin layers and the LOCO project. Continental Shelf Research.

Goodman, L. and Z. Wang, June, 2009, Turbulence observations in the northern bight of Monterey Bay from a small AUV, Journal of Marine Systems, Volume 77, Issue 4, Special issue on marine turbulence, p441-458, ISSN 0924-7963, Doi:10.1016/j.jmarsys.2008.11.004

Wang, Z. and **L. Goodman**, January, 2009a, Evolution of the spatial structure of a thin phytoplankton layer into a turbulent field. Marine Ecology Progress Series. 374:57-74 Doi:10.3354/meps07738.

Levine, E.R., **Goodman, L.,** and O'Donnell, J., 2009, Turbulence in coastal fronts near the mouth of Long Island Sounds, Journal of Marine Systems, Vol 78, Issue 3, Special issue on observational studies of oceanic fronts, 476-488, ISSN 0924-7963, DOI: 10.1016/j.jmarsys.2009.02.005.

Goodman, L. and Robinson, A.R. On the Theory of Advective Effects on Biological Dynamics in the Sea, III: The Role of Turbulence in Biological Physical Interactions, Proc Royal Soc., Proceedings A 464 (2091), Mar 08, 2008.

Goodman, L. Levine, E.R., Lueck, R. On Measuring the terms of the Turbulent Kinetic Energy Budget from an AUV, Journal of Ocean and Atmospheric Technology, July 2006, pages 977-990.